USING VACUUM FURNACES TO PROCESS 3D-PRINTED PARTS

Vacuum heat treating is a crucial step in the additive manufacturing process cycle to meet required part quality specifications.

Robert Hill, FASM,* Solar Atmospheres of Western PA, Hermitage, Pa.

Additive manufacturing (AM), or 3D printing, is a revolutionary technology that involves converting a digital model into a net- or near-net shape metallic part by building up layers of powder or wrought feedstock. Many believe AM will change the world of manufacturing, while others believe it will never replace machining, otherwise known as subtractive manufacturing. The reality probably lies somewhere between the skepticism and hype.

OPPORTUNITIES AND CHALLENGES

The possibilities and benefits of AM are exciting. A huge advantage of the process is that it uses only the material needed to make the part. In addition, unlike subtractive manufacturing, AM has no design constraints, enabling freedom of design for functionality. AM also significantly reduces the time from part design to market: Part manufacturing often begins within one hour of final design.

The various methods of additive manufacturing are truly revolutionary technologies, which present many challenges. One of the main hurdles is the high cost of equipment, where a single printer with ancillary equipment can cost roughly $1 million. Printer feedstock materials are also expensive. For example, the price of metallic powders ranges from $300/lb for alloy steel to $1200/lb for titanium alloys.

The AM field also lacks industry-wide standards. AM metallurgy consists of multiple recast layers (versus traditional metallurgy of one homogenous melt of material), which can result in many inconsistencies. Issues that need to be resolved include how individual layers of deposited material are qualified, quantified, and inspected. Acceptable levels of porosity and density must also be defined. In addition, certain processes produce parts that exhibit different mechanical properties longitudinally with the deposit and transversely across the deposit.

Therefore, the big challenge facing the AM industry is to identify new, effective quality assurance techniques. In most cases, certification and validation initiatives for AM products are being driven by primary contractors such as General Electric Aviation and Lockheed Martin. GE has spent millions of dollars on mass inking and qualifying a very intricate fuel nozzle (Fig. 1) made using direct metal laser sintering for use on next-generation LEAP (leading edge aviation propulsion) high-bypass turbofan engines. The one-piece printed fuel nozzle replaces a nozzle assembly consisting of 20 parts. The AM part is both stronger and lighter weight, and reportedly saves $1.5 billion in fuel over the life of an airplane.

*Member of ASM International

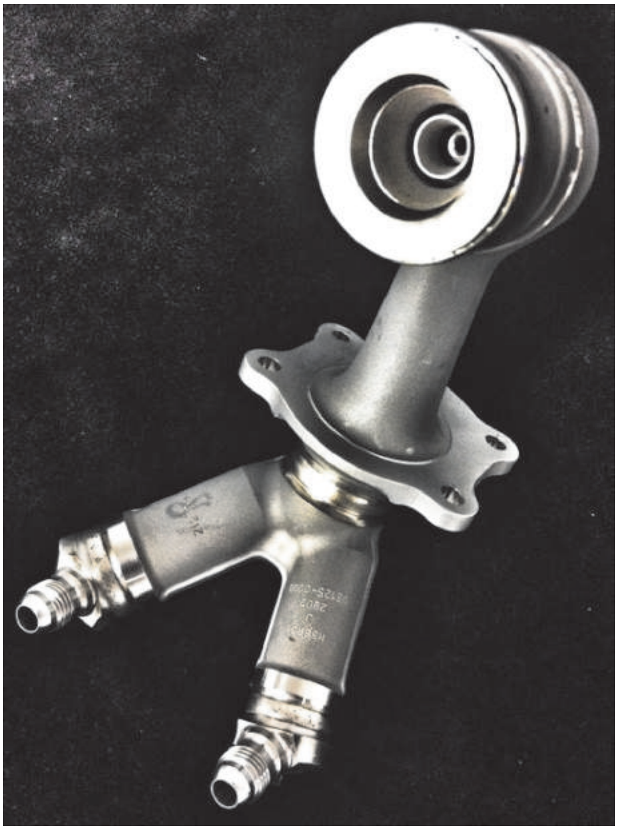

Fig. 1 — DMLS one-piece fuel nozzle is the first FAA-cleared 3D printed part to fly in a commercial jet.

ADDITIVE PROCESSES

Direct metal laser sintering (DMLS) is a process in which metal powder is injected into a high-power (400-1000 W) focused laser beam operating under tightly controlled atmospheric conditions. The laser beam melts the surface of the target material, generating a small molten pool of base material. Powder is delivered and absorbed into the pool, forming a deposit. Typically, the DMLS process is carried out in an inert chamber to control oxidation of the metallic pool. Materials processed via this method include titanium, Inconel, and cobalt-chromium alloys. The low deposition rate of DMLS enables production of fine details (Fig. 2).

Electron beam additive manufacturing (EBAM) directs a high-power electron beam to selectively fuse wire on a plate

Fig. 2 — Decorative part for the yacht "Hollow Ribbons" made using DMLS.

Fig. 3 — EBAM is used to deposit titanium wire on a titanium base.

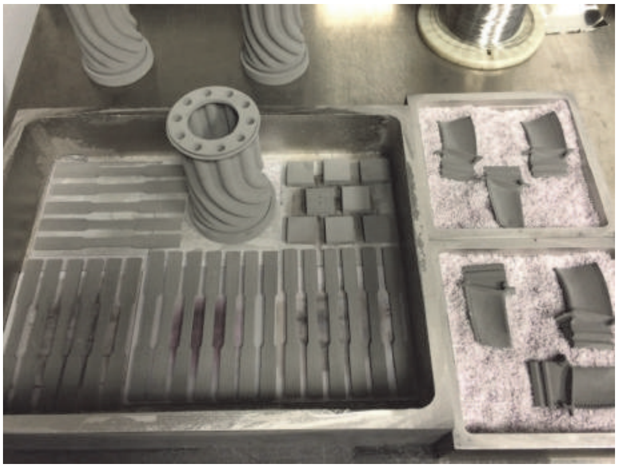

Fig. 4 — BJP-printed engine blades and other titanium alloy test pieces.

of similar material within a vacuum chamber. The process deposits material at a higher rate than DMLS, but the finished shape is not as fine. Material for EBAM parts that are vacuum heat treated is predominantly Ti-6Al-4V (Fig. 3).

Binder jet process (BJP) involves spraying a liquid binder onto a bed of powder at ambient temperature. The conglomeration of the binder and powder is solidified using a very low heat source equivalent to a heat lamp. Each layer is printed in a manner similar to a printer depositing ink on paper. The printed part is lowered after each layer solidifies until the component is complete (Fig. 4). This method has the lowest manufacturing cost of all additive processes—as much as 10 times less expensive. However, vacuum heat treating of BJP parts is more complicated.

VACUUM HEAT TREATING AM PARTS

AM is rapidly developing due to the demand for near-net shape parts with geometries that are impossible to machine. Because AM parts require very little material removal during downstream processing, it is imperative that finished parts do not have any decarburization or contaminated surfaces from subsequent thermal processing. Therefore, a crucial piece of equipment in the additive manufacturing industry is a well-maintained vacuum furnace, which operates totally devoid of oxygen, is equipped with diffusion pumps to achieve deep vacuum levels, and has very precise temperature control (Fig. 5).

One of the most important factors for successful inert vacuum heat treatment of AM parts is a leak-free furnace. Therefore, a leak rate of less than five microns per hour is imperative regardless of the chamber size. The furnace must also be thoroughly baked out at a minimum temperature of 2400°F prior to an AM furnace cycle. Overall temperature uniformity is critical for successful thermal processing of any parts, especially printed parts. For example, BJP components function as a type of thermocouple sensor. A BJP workpiece that does not reach or exceed a ±2°F temperature range exhibits a lack of temperature control in the form of excessive shrinkage or growth. Therefore, when sintering temperatures (around 2500°F) preclude attaching thermocouples to the workpiece, a Type S sensor must be strategically located within inches of the workpiece (Fig. 6). There is tremendous potential for scrap without precise temperature control.

Solar Atmospheres has processed AM parts of many shapes and sizes. The DMLS method generally requires

Fig. 5 — AM-capable vacuum furnaces range from lab size to 48 ft long.

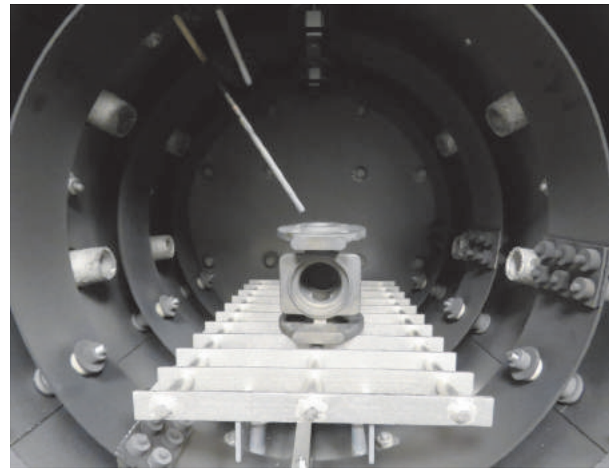

Fig. 6 — Heat treating a BJP-printed part requires precise temperature measurement.

Fig. 7 — Creep-forming is used to flatten a warped EBAM titanium baseplate by placing weights on the part during heat treatment.

three vacuum heat treating processes per various aerospace standards—vacuum annealing, vacuum aging, and vacuum stress relieving.

Typically, prior to heat treating, EBAM baseplates are severely warped due to high heat concentration of the electron beam on one side of the base material. To counteract the warping, AM companies are trying to simultaneously print on both sides of the base plate. Until the distortion can be better controlled, vacuum annealing and vacuum stress relieving processes are used to "creep form" the parts back into shape so they can be finish machined. Graphite plates, molds, and stainless steel weights are used to help accomplish this task (Fig. 7).

Because BJP involves very little heat during manufacturing, downstream heat treating is often challenging. As with metal injection molding (MIM) metallurgy, the BJP part must be fully densified by vacuum sintering. Sintering temperatures are often within 10°F of the melting point of the base material, so precise pyrometric control is critical. In addition, slow ramp-up rates and various holding times are crucial to bake off residual binders remaining within the delubed parts.

CONCLUSIONS

Global 3D printing industry revenues from products and services exceeded $2.2 billion in 2014. Revenues for the global market are expected to exceed $21 billion by the year 2020, according to the *Wohlers Report on Additive Manufacturing and 3D Printing.*

The aerospace industry is not the only niche market where AM is making its mark. AM in the medical device market has also grown significantly. The technology's geometric design freedom is particularly useful in orthopedics, enabling the design of more natural anatomical shapes while printing the porous surfaces required for bone grafting purposes.

Additive manufacturing is not yet the manufacturing panacea portrayed by its enthusiasts. Today, 3D printing is not likely to replace traditional machining, because AM only eliminates some—and not all—machining. Even the best finish produced by printing requires final machining and/or grinding, especially for parts that need to be assembled to other components. Additive manufacturing is not about forcing manufacturers and heat treaters to abandon conventional manufacturing processes used for decades. However, it offers an exciting alternative manufacturing method, especially when savings can be realized in design flexibility and fewer manufacturing steps—or even $1.5 billion in jet fuel.

For more information: Robert Hill is President, Solar Atmospheres of Western PA, 30 Industrial Rd., Hermitage, PA 16148, 724.982.0660, ext. 2224, bobh@solarwpa.com, www.solaratm.com.